US006064126A

United States Patent [19]

Beardmore

[11] **Patent Number: 6,064,126**

[45] **Date of Patent: May 16, 2000**

[54] **SWITCHES AND SWITCHING SYSTEMS**

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[21] Appl. No.: **09/043,666**

[22] PCT Filed: **Nov. 11, 1996**

[86] PCT No.: **PCT/GB96/02774**

§ 371 Date: **Aug. 24, 1998**

§ 102(e) Date: **Aug. 24, 1998**

[87] PCT Pub. No.: **WO97/18574**

PCT Pub. Date: **May 22, 1997**

[30] **Foreign Application Priority Data**

Nov. 14, 1995	[GB]	United Kingdom	9523238
Dec. 1, 1995	[GB]	United Kingdom	9524653

[51] **Int. Cl.**^{7} **H01H 1/04**; H02B 1/24

[52] **U.S. Cl.** **307/112**; 307/125

[58] **Field of Search** 307/112, 116, 307/125, 130, 131, 139, 140; 361/748, 781, 807; 257/146, 499, 234

[56] **References Cited**

U.S. PATENT DOCUMENTS

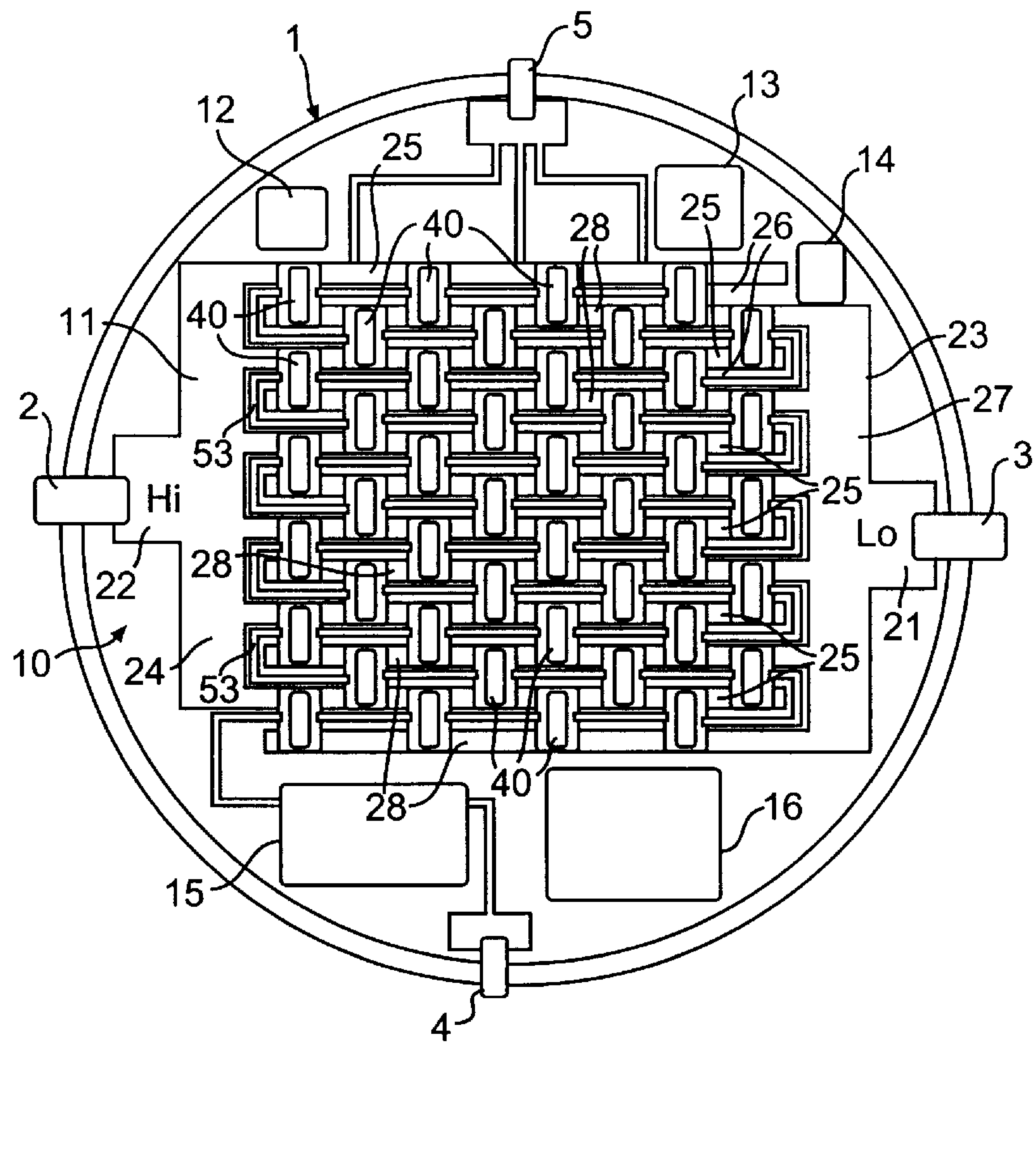
5,479,042	12/1995	James et al.	257/415
5,619,061	4/1997	Goldsmith et al.	257/528
5,637,904	6/1997	Zettler	257/417
5,794,761	8/1998	Renaud et al.	200/181

Primary Examiner—Jeffrey Gaffin
Assistant Examiner—Peter Zura
Attorney, Agent, or Firm—Pollock, Vande Sande & Amernick

[57] **ABSTRACT**

An electrical switch has an evacuated housing with input and output terminals each connected to a respective group of metal tracks extending parallel and insulated from one another. A second silicon plate is cut to form several bridging elements, each having a metal layer on its upper and lower surface. Each bridging element extends transversely above tracks connected to different ones of the terminals. The housing is closed by a silicon cap having actuating tracks extending above the bridging elements, which form an electrostatic actuator with the metal layer on the upper surface of the bridging elements. When a voltage is applied to the electrostatic actuator, the bridging elements are driven down so that they contact tracks connected to different ones of the terminals and allow current to flow between them.

9 Claims, 2 Drawing Sheets



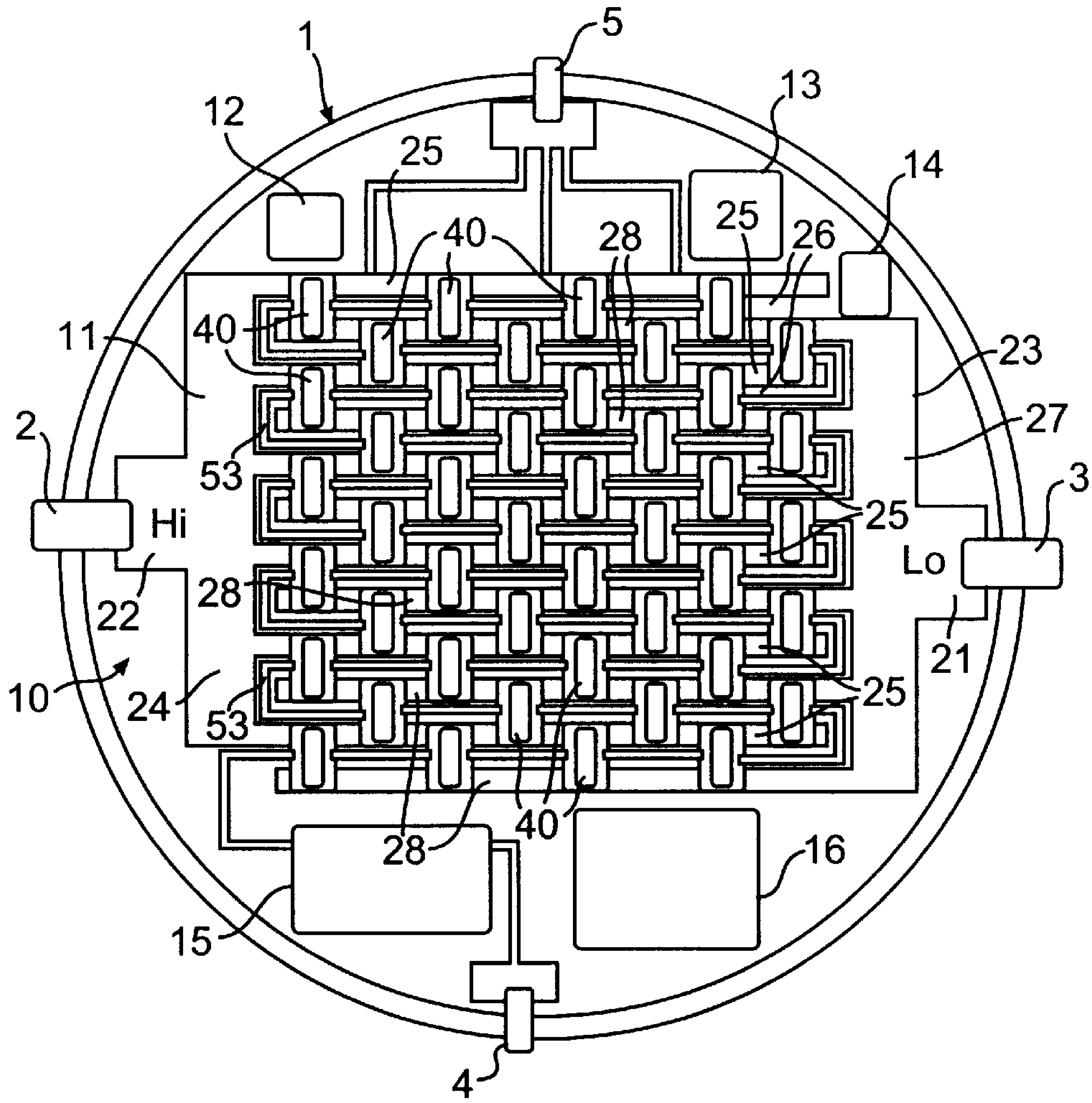


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FIG. 1

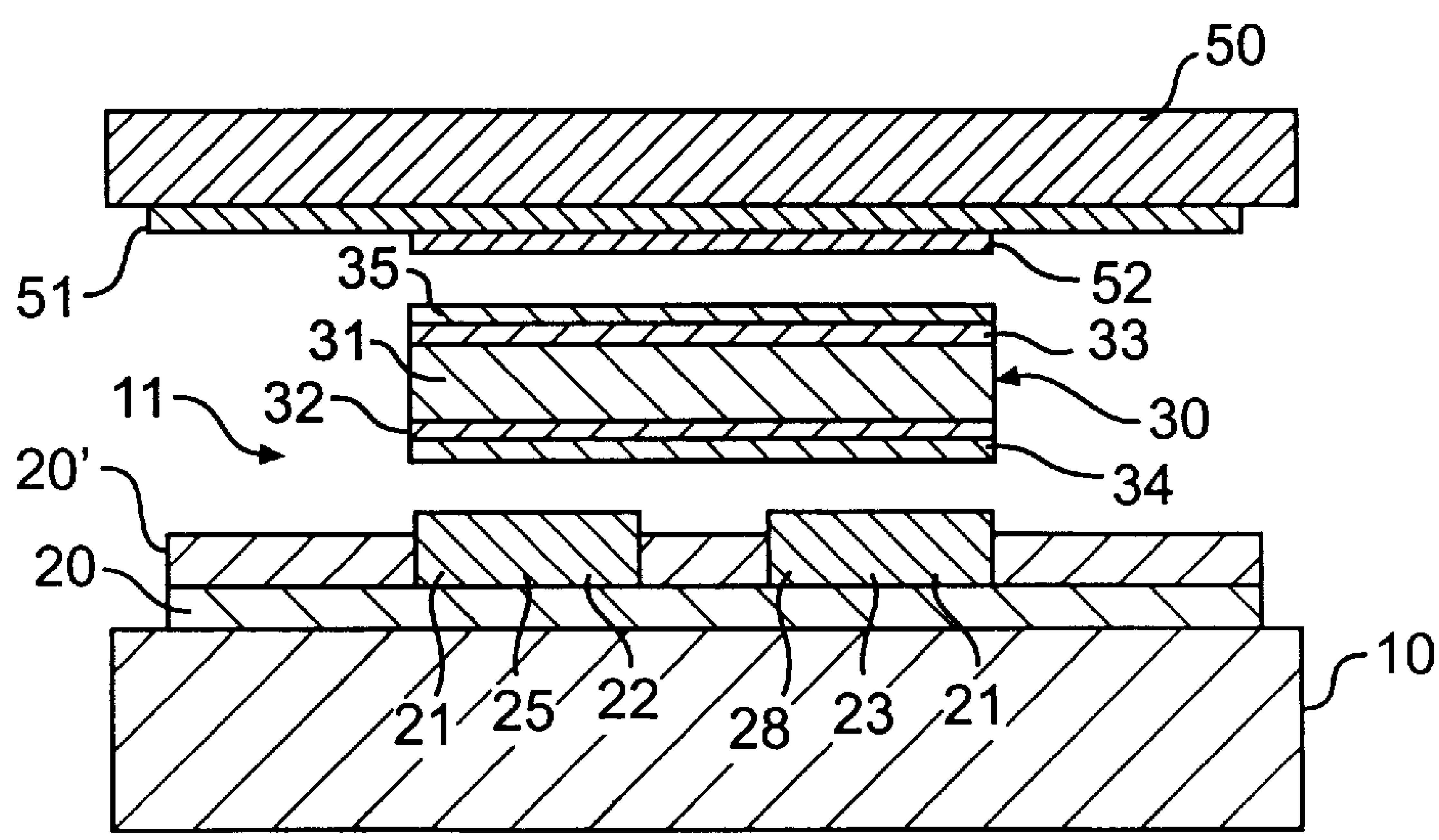

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FIG. 2

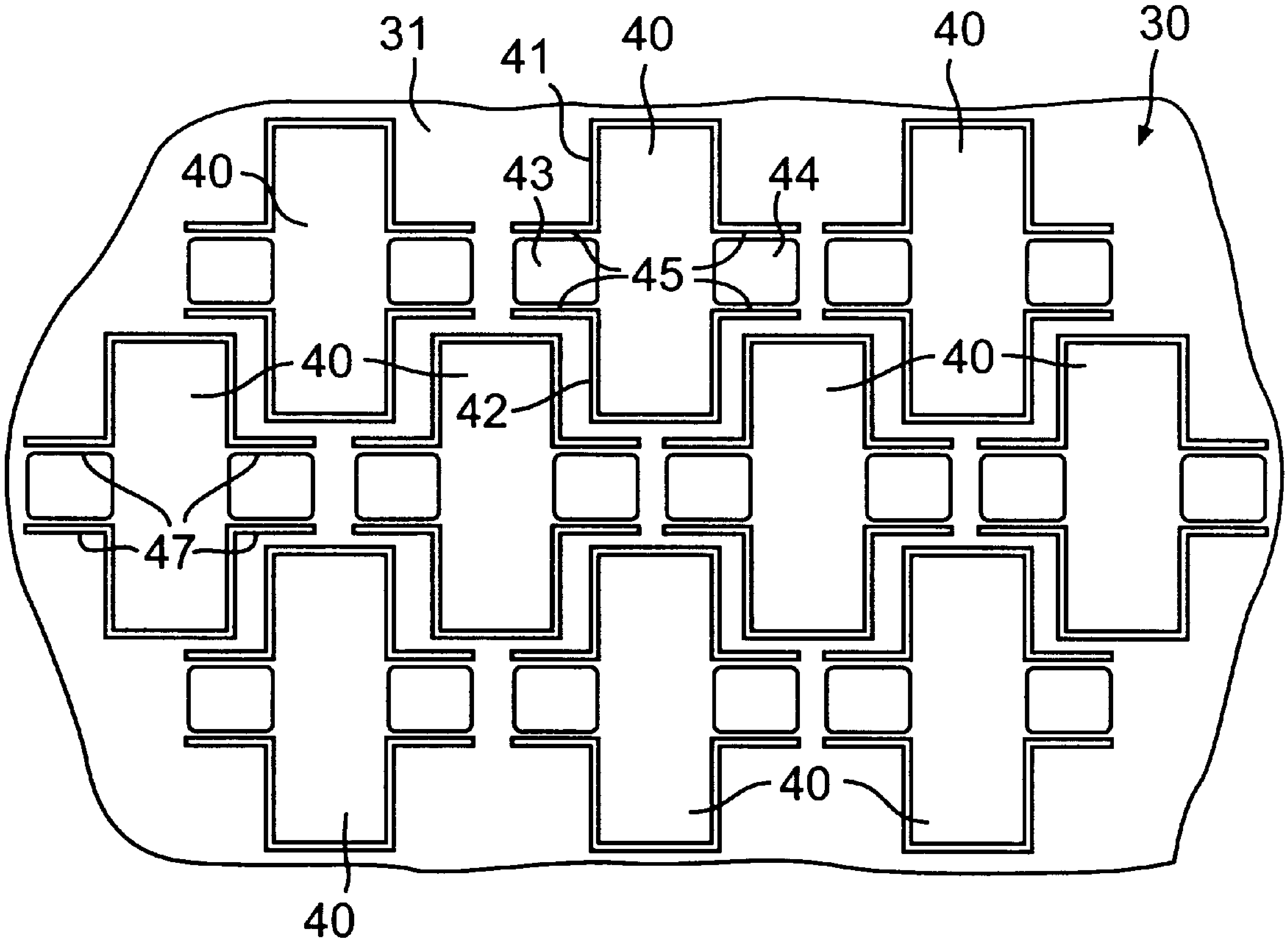

FIG. 3

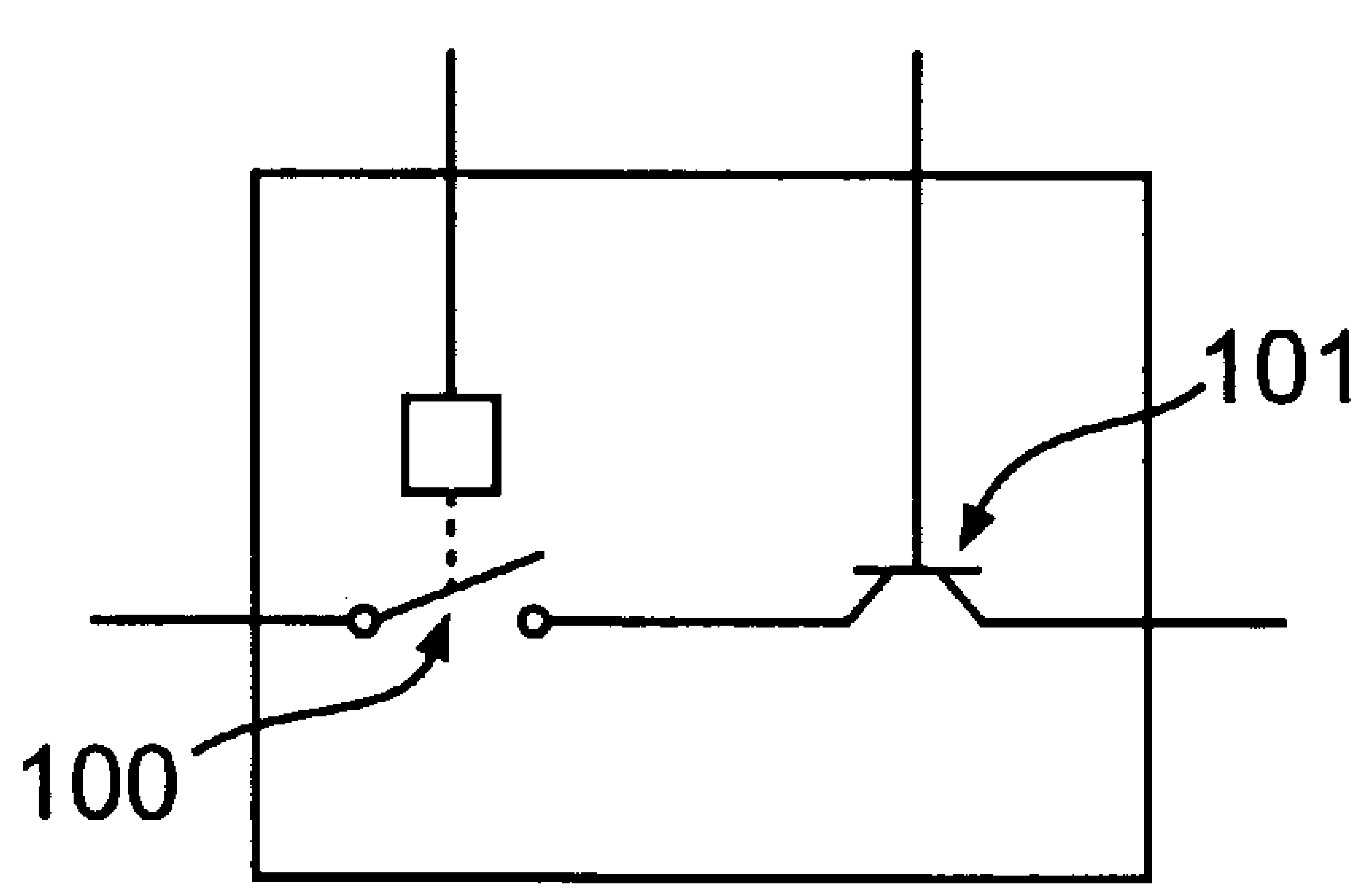

FIG. 4

SWITCHES AND SWITCHING SYSTEMS

FIELD OF THE INVENTION

BACKGROUND OF THE INVENTION

This invention relates to switches of the kind including two terminals, a plurality of conductive tracks extending from each terminal, the conductive tracks connected with one terminal being electrically insulated from the tracks connected with the other terminal, the switch including a plurality of electrically-conductive bridging elements spaced from the tracks and displaceable between a first position where the bridging elements are spaced from the tracks and a second position where each bridging elements is in contact with a track connected with one terminal and a track connected with the other terminal such that current can flow in parallel between the two terminals via the conductive tracks and the bridging elements, and an actuator arranged to displace the bridging elements between the first and second position.

The switching of high currents is usually carried out by means of an electromagnetic relay or contactor employing a solenoid to displace an armature so that it bridges or isolates two contacts, thereby allowing or preventing current flow between the terminals. These relays can operate reliably but require relatively high currents to operate the solenoid. They are also bulky and heavy, and respond relatively slowly because of the mass of the armature. Lower currents can be switched using semiconductor devices such as FETs and thyristors but these have the disadvantage of introducing a voltage drop across the device and of not being suitable for higher current operation. U.S. Pat. No. 5,430,597 describes a current interrupting device of the above-specified kind having parallel branches extending from input and output lines, which are bridged by a number of micromechanical switches.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide an improved form of switch.

According to one aspect of the present invention there is provided a switch of the above-specified kind. At least some of the bridging elements are formed in a common plate of material that is fixed and is formed to provide flexible elements by which the bridging elements are supported in the plate, such that each bridging element is independently flexible relative to the plate and failure of one bridging element in the second position does not prevent other bridging elements moving to the first position.

The upper surface of each track and the lower surface of each bridging element is preferably flat, the bridging elements in the lower position contacting the tracks across their entire width. The plate may be of silicon, the bridging elements having an electrically-conductive layer arranged to contact the tracks when the bridging elements are displaced to their second position. The bridging elements may be of rectangular shape, the flexible elements being a pair of flexure elements extending outwardly of each bridging element on opposite sides midway along its length. The actuator is preferable an electrostatic actuator. The conductive tracks and bridging elements are preferably located in an evacuated housing. The conductive tracks may extend on a silicon substrate. The conductive tracks may extend on a layer of diamond, the layer of diamond extending on a substrate of a different material.

According to another aspect of the present invention there is provided a switching system including a first switch according to the above aspect of the invention and a second semiconductor switch connected in series with the first switch.

BRIEF DESCRIPTION OF THE DRAWINGS

A switch and a system including a switch according to the present invention, will now be described, by way of example, with reference to the accompanying drawings, in which:

FIG. **1** is a plan view showing a lower wafer of the switch and the location of the bridging elements of the switch;

FIG. **2** is a cross-sectional transverse view of a part of the switch to an enlarged scale;

FIG. **3** is a plan view of a central wafer of the switch; and

FIG. **4** is a schematic diagram of a system including the switch.

DETAILED DESCRIPTION OF THE INVENTION

With reference first to FIG. **1**, the switch has a sealed and evacuated outer housing **1** of circular shape through which project: two metal power terminals **2** and **3**, an actuation terminal **4** by which the switch is controlled, and a fourth terminal **5** connected to various sensors within the switch by which its operation can be monitored.

Within the housing **1** there is a circular silicon substrate or wafer **10**, on which is formed the switching assembly **11** and associated components such as arc suppression diodes **12**, a thermal sensing and processing unit **13**, a getter heater film and micro heater **14** to improve the vacuum within the switch, signal buffer circuitry and switching logic **15**, and additional processing **16**. The switching assembly **11** and associated components **12** to **16** may all be formed by conventional integrated circuit or microengineering techniques in the silicon wafer **10** or in layers deposited on the wafer. Alternatively, they could be separate, discrete components.

Referring now also to FIGS. **2** and **3**, the switching assembly **11** is formed in a central region of the silicon wafer **10** and comprises a first electrically-insulative layer **20**, such as of diamond, formed on the upper surface of the wafer. On top of the layer **20** there is deposited an electrically-conductive layer **21** of a metal such as silver. The conductive layer **21** is divided into two regions **22** and **23**, which are normally electrically isolated from one another. One region **22**, shown on the left of FIG. **1**, is connected with the terminal **2** and has a lateral arm **24** and six straight, parallel bus bars **25** in the form of fingers extending longitudinally to the right of the wafer. The bus bars **25** are spaced from one another by five gaps **26**. The other region **23** of the conductive layer **21** has the same shape as the left-hand region **22** with a lateral arm **27** connected with the other power terminal **3** and with six bus bars **28** extending to the left and interdigitated with the bus bars **25** of the left-hand region **22**. The two sets of bus bars **25** and **28** extend parallel with one another and are spaced from one another by gaps so that they are electrically isolated from ore another. As shown in FIG. **2**, the gap between the bus bars **25** and **28** is preferably filled to a level just below their upper surface with a second diamond layer **20'**; both the layers **20** and **20'** are electrically non-conductive but are thermally conductive.

A second, thin central silicon wafer **30** is mounted on the lower wafer **10** with its central region spaced above the lower wafer. The central wafer **30** is not shown in full in FIG. **1** or **2** but is shown most clearly in FIG. **3**. The central wafer **30** comprises a silicon plate **31** having electrically-insulative layers **32** and **33** of a silicon oxide on its lower and upper surfaces. On top of the insulative layers **32** and **33** are deposited respective electrically-conductive layers **34** and **35** of a metal, such as silver. The central wafer **30** is machined through its thickness by micro-engineering techniques, such as etching or erosion, to give the pattern shown in FIG. **3** and form the wafer into forty-four bridging elements **40** of which only ten are shown in FIG. **3**. Each bridging element **40** is of rectangular shape and is formed by two linear cuts **41** and **42** and two apertures **43** and **44**. The linear cuts **41** and **42** form three sides of a square and two outwardly-projecting limb elements **45**, to define the boundary of the bridging element **40**. The apertures **43** and **44** are formed between the limb elements **45** of the two cuts **41** and **42**, the size of the apertures and the spacing of the limb elements forming a pair of narrow flexure elements **47** on opposite sides extending parallel with one another at right angles to the bridging element **40** midway along its length. It can be seen that the cuts **41** and **42**, and the apertures **43** and **44** separate the bridging element **40** from the remainder of the central wafer **30** except for the four flexure elements **47**, which support the bridging elements in the wafer. These flexure elements **47** enable the bridging element **40** to be displaced vertically up or down relative to the plane of the central wafer **30** when acted on by an external force. The positioning of the bridging elements **40** is shown in FIG. **1** and it can be seen from this that the elements are oriented transversely to the bus bars **25** and **28** and extend between a bus bar **25** of one region **22** and a bus bar **28** of the other region **23**, bridging the gap between them. The bridging elements **40** are arranged in eleven groups of four elements, each group of elements being located above the same two bus bars and being equally spaced along their length.

A third, upper silicon wafer **50** is mounted above the lower wafer **10** and the central wafer **30**. The upper wafer **50** is preferably in the form of a cap sealed about its outer edge to the lower wafer **10** so as to enclose the various component **3**. On the underside of the upper wafer **50**, there is an electrically-insulative layer **51** and a eight metal actuating tracks **52** extending transversely of the bus bars **25** and **28** and aligned with the bridging elements **40**. The tracks **52** are electrically connected with a track **53** on the lower wafer, which is in turn connected to the control terminal **4** via the buffer circuit **15**. The upper conductive layer **35** on the central wafer **30** is also connected to the buffer circuit **15**. The tracks **52** on the wafer **50** and the conductive layer **35** on the bridging elements **40** together form an electrostatic actuator for displacing the bridging elements.

In the natural state of the switch, the bridging elements **40** are in a first position equally spaced between the bus bars **25** and **28** and the actuating tracks **52**, so that they do not contact either the lower wafer **10** or the upper wafer **50**. In this natural state of the switch, no current can flow between the two power terminals **2** and **3**, so the switch is off or open.

In order to close the switch, a signal is applied to the actuation terminal **4**. This causes the circuit **15** to apply a voltage of the same polarity to both the actuating tracks **52** and to the actuating electrodes formed by the conductive layer **35** on the upper surface of the bridging elements **40**. This produces a repulsive electrostatic force between the tracks **52** and the bridging elements **40**, thereby driving the bridging elements down into their second position, in contact with the bus bars **25** and **28** on the lower wafer **10**. This, therefore, causes the bridging elements **40** to bridge the bus bars **25** and **28** connected to the different terminals **2** and **3**, allowing current to flow between the terminals. To open the switch, a different signal is applied to the actuation terminal **4**, causing the circuit **15** to apply voltages of opposite polarities to the actuating tracks **52** and the actuating electrodes **35** so that the bridging elements **40** are pulled upwardly above their natural position. The voltages are then removed so that the bridging elements **40** can return to their natural central position. The flexure mounting **47** of the bridging elements **40** allows the elements to tilt so that they can accommodate geometric irregularities of the bus bars.

The use of multiple bridging elements, each connected in parallel with one another, means that each element need only be capable of conducting a corresponding fraction of the total current passed by the switch. Ideally, each bridging element would pass the same current, however, in practice, manufacturing variations and other factors may lead to some elements passing a greater current than others. Providing, however, that the conductors in the switch have a positive temperature coefficient, this increased current leads to an increase in temperature of the conductors in series with the bridging element and hence an increase in the resistance and a corresponding reduction in current. The low thermal mass of the different elements of the switch means that this self-regulating effect will be very rapid. The bridging elements **40** can have a very small size and low inertia giving the switch a very high switching speed. The switch is a true mechanical switch so it has a low contact resistance and a high open resistance compared with a semiconductor switch. Where very high currents need to be passed, several switches can be stacked together so that they operate in parallel. The switch can be made in volume at low cost and can have a high resistance to vibration and shock. Also, the switch can operate silently and it produces only low levels of electromagnetic interference. The design is fault tolerant since the failure of one bridging element to make contact would not significantly affect operation. If one element should fail to break contact, it would simply fuse and this section of the switch would go open circuit. The fusing current of one bridging element is selected to be less than the fusing current of a bus bar. By operating the bridging elements in a high vacuum free of organic matter, there is a maximum insulation, arc suppression and life. The vacuum also eliminates windage effects and squeeze film damping so that switching times are minimized.

The layout of the bus bars **25** and **28** over the surface of the wafer **10** distributes the current carrying and current switching across the surface of the wafer so as to spread the thermal load. The thermal sensor **13** is used to monitor the temperature within the switch and to cause the switch to open if temperature should rise above a safe level.

The actuator need not be of an electrostatic kind, alternatively, it could be piezoelectric thermal or the like. The natural state of the switch could be closed, the actuator being energized to open the switch

The mechanical switch of the present invention could be connected in series with a conventional semiconductor power switch, as shown in FIG. **4**, to form a switching system. In this arrangement a mechanical switch of the kind described above is indicated by the numeral **100** and this is connected in series with a power switching transistor. or the like. **101**. The transistor **101** would be opened first so that the voltage is held off the mechanical switch **100** while this breaks and maintains a gap. The advantage of this is that it would reduce the risk of break-down in the vacuum within the mechanical switch **100**, between the bridging elements **40** and the bus bars **25** and **28** as the gap opens. Once open, the mechanical switch **100** would prevent leakage current through the semiconductor switch **101**. This system would also have the advantage of redundancy. The mechanical switch **100** would act as a fall back and a fuse if the transistor **101** should fail in a conducting state. The transistor **101** would act as a circuit breaker if the mechanical switch **100** should become stuck in a conducting state. The mechanical switch **100** and the semiconducting switch **101** could be formed on the same wafer.

What is claimed is:

1. An electrical switch for enabling or preventing current flow between two points wherein the switch includes two terminals, a plurality of conductive tracks extending from each terminal, the conductive tracks connected with one terminal being electrically insulated from the tracks connected with the other terminal, the switch including a plurality of electrically-conductive bridging elements spaced from the tracks and displaceable between a first position where the bridging elements are spaced from the tracks and a second position where each bridging element is connected with one terminal and a track connected with the other terminal such that current can flow in parallel between the two terminals via the conductive tracks and the bridging elements, and an actuator arranged to displace all the bridging elements together between the first and second position, such that all the bridging elements are either in the first or second position at any one time, wherein at least some of the bridging elements are formed in a common plate of material that is fixed and is formed to provide flexible elements by which the bridging elements are supported in the plate, such that each bridging element is independently flexible relative to the plate and failure of one bridging element in the second position does not prevent other bridging elements moving to the first position.

2. A switch according to claim **1**, wherein the upper surface of each track and the lower surface of each bridging element is flat, and that, in the second position, the bridging elements contacts the tracks across the entire width of the tracks.

3. A switch according to claim **1**, wherein the plate is of silicon and the bridging elements have an electrically-conductive layer arranged to contact the tracks when the bridging elements are displaced to their second position.

4. A switch according to claim **1**, wherein the bridging elements are of rectangular shape, and that the flexible elements are a pair of flexure elements extending outwardly of each bridging element on opposite sides midway along the length of the bridging element.

5. A switch according to claim **1**, wherein the actuator is an electrostatic actuator.

6. A switch according to claim **1**, wherein the conductive tracks and the bridging elements are located in an evacuated housing.

7. A switch according to claim **1**, wherein the conductive tracks extend on a silicon substrate.

8. A switch according to claim **1**, wherein the conductive tracks extend on a layer of diamond, and that the layer of diamond extends on a substrate of a different material.

9. A switch according to claim **1** including a second semiconductor switch connected in series with the switch.

* * * * *

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 6,064,126
DATED : 05/16/00
INVENTOR(S) : Geoffrey Beardmore

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

The name of the Assignee has been omitted. Section [73] should be added as follows:

[73] Assignee: **Smiths Industries Public Limited Company,** London, United Kingdom

Signed and Sealed this

First Day of May, 2001

Attest:

Nicholas P. Godici

NICHOLAS P. GODICI

Attesting Officer *Acting Director of the United States Patent and Trademark Office*

UNITED STATES PATENT AND TRADEMARK OFFICE

CERTIFICATE OF CORRECTION

PATENT NO. : 6,064,126
DATED : May 16, 2000
INVENTOR(S) : Geoffrey Beardmore

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Section [73] should be added as follows:

[73] Assignee: **Smiths Industries Public Limited Company,** London, United Kingdom

Signed and Sealed this

Eighteenth Day of September, 2001

Attest:

Nicholas P. Godici

NICHOLAS P. GODICI

Attesting Officer

Acting Director of the United States Patent and Trademark Office